Towards an Understanding of the Globular Cluster Over–abundance around the Central Giant Elliptical NGC 1399

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ABSTRACT

We investigate the kinematics of a combined sample of 74 globular clusters around NGC 1399. Their high velocity dispersion, increasing with radius, supports their association with the gravitational potential of the galaxy cluster rather than with that of NGC

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1399 itself. We find no evidence for rotation in the full sample, although some indication for rotation in the outer regions. The data do not allow us to detect differences between the kinematics of the blue and red sub-populations of globular clusters. A comparison between the globular cluster systems of NGC 1399 and those of NGC 1404 and NGC 1380 indicates that the globular clusters in all three galaxies are likely to have formed via similar mechanisms and at similar epochs. The only property which distinguishes the NGC 1399 globular cluster system from these others is that it is ten times more abundant. We summarize the evidence for associating these excess globulars with the galaxy cluster rather than with NGC 1399 itself, and suggest that the over–abundance can be explained by tidal stripping of neighboring galaxies and subsequent accumulation of globulars in the gravitational potential of the galaxy cluster.

Subject headings: globular clusters: general , galaxies: elliptical and lenticular, cD, galaxies: halos , galaxies: kinematics and dynamics, galaxies: formation, galaxies: evolution

1. Introduction

Extragalactic globular clusters have in recent years established themselves as potential tracers of the formation and evolution of galaxies (see Ashman & Zepf 1998 for a recent review). The number of detailed photometric studies has rapidly increased, and these studies reveal a number of interesting connections between globular cluster systems and their host galaxies. With the recent commissioning of 10m–class telescopes, measuring absorption line indices of a large number of individual globular clusters has become feasible (Kissler-Patig et al. 1998; Cohen, Blakeslee, & Ryzhov 1998). Colors, magnitudes, total numbers, spatial distributions, radial density profiles, ages, and metallicities, can now be obtained and used to constrain the formation history of globular clusters and their host galaxies.

Another essential source of information for discriminating between different formation scenarios is the kinematics of globular cluster systems, as determined from the measured radial velocities of individual clusters. For example, the studies of M87 and NGC 1399 found a significantly higher velocity dispersion for the globular clusters than for the stars (Huchra and Brodie 1987; Mould et al. 1990; Brodie and Huchra 1991; Grillmair et al. 1994; Cohen & Ryzhov 1997; Minniti et al. 1998; Kissler-Patig et al. 1998). Mould et al. (1990) demonstrated that, in M87, this was consistent with the the surface density distribution of globular clusters being more extended than the surface density distribution of stars. Grillmair et al. (1994) suggested that the globular clusters around NGC 1399 were reacting to the gravitational potential of the Fornax cluster as a whole rather than just that of the host galaxy. In NGC 5128, Harris et al. (1988) and Hui et al. (1995) reported rotation in the globular cluster system, though only for the metal–rich clusters. This is contrary to the findings in NGC 4472 (Sharples et al. 1998) and M87 (Kissler-Patig & Gebhardt 1998) in which the metal–poor globular clusters seem to dominate the rotation.

Unfortunately, few models exist to compare with the (still sparse) data. Predictions for the kinematic signature in globular cluster systems after spiral–spiral mergers have been presented by Hernquist & Bolte (1992). They studied the kinematics of globular clusters already present in the progenitors and found that in the merger product these clusters are expected to be on radial orbits in the inner regions and to show some systemic rotation far out. The kinematics of globular clusters that might have formed during a merger was not addressed in their study; it would depend on the kinematics of the in-falling gas from which they formed. Other simulations (e.g. Muzzio 1987) studied the accretion and stripping of globular clusters in galaxy clusters, but no clear predictions for the kinematics of accreted globular clusters were formulated.

The primary goal of the present paper is to combine all existing kinematic data on the globular cluster system of NGC 1399 to better constrain its origin. A secondary aim is to use the photometric properties of globular clusters in the brightest Fornax galaxies to further constrain formation scenarios. The sample of radial velocities for globular clusters around NGC 1399 is compiled and presented in Sect. 2. These are used to investigate the kinematic properties of the full sample, as well as sub–samples selected on the basis of radius and color in Sect. 3. In Section 4 we compare the kinematics of the globular clusters with those of the stars, cluster galaxies and X-ray gas, and derive the mass-to-light ratio in the outer environs of the galaxy. In Sect. 5 we compare the properties of the globular clusters in NGC 1399 with those of the globular cluster systems of the next two brightest early–type galaxies in Fornax, NGC 1380 and NGC 1404. We then discuss the implications for different formation scenarios. A summary and our conclusions are given in Sect. 6.

2. The data

Our sample is based on the compilations of Grillmair (1992), Grillmair et al. (1994), Minniti et al. (1998), and Kissler-Patig et al. (1998). Briefly, the data from Grillmair et al. were obtained at the Anglo–Australian Telescope with the Low–Dispersion Survey Spectrograph and the Image Photon Counting System in the wavelength range 3800–4800 Å with $\simeq 13$ Å resolution. Minniti et al. obtained their data with the New Technology Telescope at the European Southern Observatory, using the ESO Multi–Mode Instrument in the wavelength range 6000–9000 Å with a resolution of 7.5 Å. Kissler-Patig et al. observed with the Low Resolution Imaging Spectrograph on the Keck 1 Telescope; their spectra covered a wavelength range from about 4000 Å to 6100 Å with 5.6 Å resolution. We refer the reader to the original papers for a more detailed description of the observations, the data reduction, and the velocity measurements.

Hereafter, we will refer to the respective samples as the AAT sample (Grillmair 1992, Grillmair et al. 1994), the NTT sample (Minniti et al. 1998), and the Keck sample (Kissler-Patig et al. 1998). The combined sample of 74 globular clusters is listed in Table 1. For each globular cluster we give the ID number (taken from the papers with the prefix aat/ntt/keck added respectively), the equatorial coordinates (B1950), the heliocentric radial velocity (with the weighted mean when multiple measurements were available), as well as the available photometric information. For 52 globular clusters V$-$I colors accurate to 0.035 mag where obtained from the work of Kissler-Patig et al. (1997a). The B_j magnitude and B_j-R color were taken from Grillmair (1992). We included in our combined sample all objects with radial velocities greater than 500 km s^{-1} and less than 2500 km s^{-1} (i.e. within 3σ of the mean). A list of positions, velocities and colors of the 74 globular clusters in electronic form is available from the first author. Figure 1 shows the positions with respect to NGC 1399 of all globular clusters observed; the symbols are proportional to the difference between the globular cluster velocity and the systemic velocity of NGC 1399. The two pairs of larger circles (continuous and dashed lines) show 1 and 5 $r_{\rm eff}$ for the stellar light distribution of NGC 1399 (centered) and NGC 1404 (in the SE), respectively. In Table 2 we list the adopted properties of the three brightest early-type galaxies in the center of Fornax: NGC 1399, NGC 1404, and NGC 1380.

3. Kinematic properties of the sample

3.1. Velocity distribution of the full sample

Figure 2 shows a histogram of the globular cluster velocities. As already noted by Minniti et al. (1998), the velocity distribution exhibits two peaks roughly centered on the systemic velocity of NGC 1399, although a single Gaussian cannot be rejected at better than the 95% confidence level according to a χ^2 or a Kolmogorov-Smirnov test. The mean velocity of the combined sample of globular clusters is 1429 ± 45 km s^{-1}, similar to the velocity derived for the stellar component (see Table 2). No rotation is detected in the combined sample. The maximum rotation along any axis is found to be 74 ± 107 km s^{-1}. A possible cause for the double peak in the velocity distribution may be contamination of the sample by globulars belonging to NGC 1404 or NGC 1380. We discuss this possibility further below.

3.2. Spatial distribution of the velocities

In Figure 3 we plot the cluster velocities against projected radius from the center of NGC 1399. The mean velocity does not change significantly with radius (see also Table 3). However, we note that within 4′ the velocities seem to cluster around the mean velocity of the stellar component of NGC 1399, whereas beyond 5′ the globular clusters seem to have either significantly higher or lower velocities than the mean. This is better illustrated in Fig. 4, where we have plotted histograms of the velocities in concentric annuli. Using the ROSTAT package (Beers et al. 1990, Bird & Beers 1993), we tested the samples for normality and unimodality. While the globular clusters in the inner ring are consistent at the 98% confidence level with a normal distribution, the statistics are inconclusive in the middle ring and inconsistent with normality in the outer ring at the 90% confidence level. However, the number statistics are rather small, and the distribution in the outermost annulus is only consistent with multi-modality at the 80% confidence level.

It seems reasonable to question whether beyond 6′ one is starting to sample globular clusters belonging to NGC 1404, which lies only 9′ in projection from NGC 1399. The answer comes from Fig. 1: there is no obvious sign of any concentration of high velocity clusters in the direction of NGC 1404. The second velocity peak is therefore probably not due to contamination of the sample by globular clusters belonging to NGC 1404. The recently derived density profile for the globular clusters around NGC 1404 (Forbes et al. 1998) indeed shows that contamination of our sample by NGC 1404 clusters is likely to be small; halfway between NGC 1399 and NGC 1404, the surface density of globular cluster belonging to NGC 1399 is $\simeq 40$ times higher than that of NGC 1404. Even at 5 $r_{\rm eff(NGC1404)}$ ($\simeq 2.5'$) from NGC 1404 the contribution of the two galaxies is still equal. This makes it unlikely for NGC 1404 clusters to strongly influence our sample. However, we cannot exclude the possibility that some of the globular clusters in our sample may have been stripped from NGC 1404 or NGC 1380 at some point in the past (see Sect. 5.3).

3.3. Rotation of annular sub-samples

We have searched for evidence of rotation in various annular sub-samples. No significant rotation is found in the inner regions. However, in the outer regions (>5′) we find a maximum rotation amplitude of 153 ± 93 km s^{-1} along a position angle 120 ± 40 degrees (east of north), roughly along the isophotal major axis of NGC 1399 ($\simeq$ 100 degrees, extrapolating from the measurements of Goudfrooij et al. 1994). Figure 5 shows the velocities of globular clusters with projected radii greater than 5′ versus their position angles. The velocity profile predicted by the rotation amplitude computed above is shown superimposed. We ran Monte Carlo simulations (1000 realizations, computing random data points with the same velocity dispersion, velocity errors and position angles as spanned by our sample) to estimate the significance of this result: the hypothesis of no rotation for this sample is ruled out at the 95% confidence level.

Ostrov et al. (1993), Kissler-Patig et al. (1997a) and Forbes et al. (1998) found the color distribution of NGC 1399 globular clusters to exhibit two distinct peaks. We split the sample into red and blue globular clusters (at V−I = 1.05, following Kissler-Patig et al. 1997a). The small number statistics do not allow us to see any difference in the kinematics of the blue and red samples. We only note that our sample is dominated by red clusters inside 5′ (mean V−I = 1.16 ± 0.02, where the error is the standard error of the mean), while blue and red clusters are about equal in number beyond 5′ from the center of NGC 1399 (mean V−I = 1.04 ± 0.04).

In summary, rotation of the NGC 1399 globular cluster system as a whole cannot account for the possibly double-peaked nature of the velocity histogram. However, we cannot rule out relatively high angular momentum orbits among a subset of the sample clusters. Such orbits would be a natural consequence of tidal interactions or mergers of cluster galaxies passing through the core of the Fornax cluster (cf. below).

3.4. Mean velocities and velocity dispersions of the globular clusters

The mean velocities and velocity dispersions of globular clusters reported in previous studies (the AAT, NTT, and Keck samples) are given in Table 3, together with the values for our combined sample and the various sub-samples discussed in previous sections. The mean velocity and velocity dispersions were computed using a maximum likelihood dispersion estimator (see Pryor & Meylan 1993). The dispersions of the different samples around a fixed mean (taken to be the mean of the full sample, i.e., 1429 km s^{-1}) are also given. We find that the velocity dispersion measured for the combined sample agrees with those derived individually for the AAT, NTT, and Keck samples.

More interesting is the fact that the velocity dispersion increases with radius. This behavior is clearly shown by a locally-weighted, scatter-plot smoothing fit to the velocity deviation squared (LOWESS, see Cleveland & McGill 1984, as implemented by Gebhardt et al. 1994) and shown as a solid line in Fig. 6, on top of the data for the globular clusters. Also shown in Fig. 6 are the measured velocity dispersions of the stars, the planetary nebulae, and the Fornax cluster galaxies.

4. Dynamics

4.1. Are the Stellar and Globular Cluster Measurements Inconsistent?

The difference between the line-of-sight velocity dispersions of the globular clusters and the stars could be explained by very different density profiles of the two components, or by different degrees of anisotropy. Wagner et al. (1991), Bridges et al. (1991), Kissler-Patig et al. (1997a) and Forbes et al. (1998) found little or no difference in the surface density profiles of the stars and the globular clusters, accounting for <10% of the difference in the velocity dispersions. A difference in the degree of anisotropy is not excluded and assuming the stellar velocity dispersion to be isotropic, the higher velocity dispersion of the globular clusters would require that the tangential velocity dispersion of the globular cluster system is at least 30% larger than its radial component (following Mould et al. 1987). However, given that the stellar and globular cluster data are sampling different radial regimes, we could equally well postulate that the stars and the globular clusters are both isotropic systems. In this case, the differences in the measured velocity dispersions of the stars and the globular clusters would arise from a strong increase in the potential field strength with radius. As we show below, even assuming the extreme case that all globular clusters are on circular orbits, we find a mass-luminosity ratio several times larger than that which has been derived for the stellar component within 1.5′ of NGC 1399.

4.2. Can M/L be Constant?

The spectroscopic measurements of the integrated stellar light almost reach the range in radius where the innermost globular clusters are measured. Together with the data for the planetary nebulae, there is a consistent indication of a marked up-turn in the velocity dispersion between 1′ and 3′ from NGC 1399. This is seen independently in each of the stellar, planetary nebula, and globular cluster data. Regardless of whether the orbit shapes are changing or the Fornax cluster potential is becoming dominant, this suggests that all luminous components are similarly affected. This is not a trivial result; whereas we find only little evidence for rotation in the globular cluster system, Arnaboldi et al. (1994) claim that the system of planetary nebulae exhibits a rotation amplitude of ~ 250 km s^{-1} with a PA $\simeq -35°$, i.e. counter-rotating with respect to the globular clusters. If real, this might constitute an important clue concerning the manner in which the cD envelope of NGC 1399 was built up.

Following Grillmair et al. (1994), we determine whether or not the increase in the measured velocity dispersion at larger radii must be attributed to an increase in M/L by assuming the extreme case that all of our observed globular clusters are on perfectly circular orbits (which for a given potential field strength will produce the largest observed line-of-sight velocity dispersion). Assuming a spherical distribution of mass in hydrostatic equilibrium, and that the surface density of globular clusters and the stellar light both follow the surface brightness parameterization of Killeen & Bicknell (1988), we use Equations (2) and (3) of Grillmair et al. (1994) to solve in a least-squares sense for a radially-invariant M/L ratio. Sampling the velocity dispersion profile over the same distribution of projected radii as in our combined sample, we find that our observations are best fit using $M/L_B = 50 \pm 15$ $M_\odot/L_\odot$, where the quoted error reflects only the uncertainty in velocity dispersion computed for the full sample in Table 3.

In a way similar to Minniti et al. (1998) we use the projected mass estimator (Heisler et al. 1985), under the hypothesis of a spherical distribution of matter and isotropy of the velocity dispersion. For the 74 globular clusters, we obtain $M_P = 1.0 \times 10^{13}$ $M_\odot$. This mass estimate, along with $L = 4.8 \times 10^{10}$ $L_\odot$ (Grillmair et al. 1994, scaled to our adopted distance), gives $M_P/L \sim 208$. The error in this quantity is dominated by the small sample size and the different underlying theoretical assumptions. E.g., adopting radial instead of isotropic orbits for the globular clusters increases the mass estimate by a factor of two.

Other mass estimators (Heisler et al. 1985) applied to the same sample give the following results: the virial mass $M_{VT} = 8.0 \times 10^{12}$ $M_\odot$ implies $M_{VT}/L \sim 167$, the median mass $M_M = 6.6 \times 10^{12}$ $M_\odot$ implies $M_M/L \sim 138$, and the average mass $M_{AV} = 7.8 \times 10^{12}$ $M_\odot$ implies $M/L \sim 162$. The virial, projected, and average masses share the same sensitivity to interlopers, i.e., globular clusters from the intracluster medium or from the nearby galaxies. Eliminating from the sample even a single such object can decrease the M/L values by as much as 30% (Minniti et al. 1998). These M/L values, obtained from the globular cluster system of NGC 1399, are similar to the corresponding values obtained with the same mass estimators by Huchra & Brodie (1987) from the globular cluster system of M87.

Contrary to the velocity dispersion determinations, which suffer only from the observational errors on the radial velocities, the mass-to-luminosity estimates accumulate the errors associated with many various observed parameters, such as the total luminosity within a given radius, the distance modulus and the radial velocity of the host galaxy, not to mention the different theoretical assumptions. Nevertheless, all our M/L determinations (50 – 200) are larger than that of a typical old stellar population ($1 < M/L < 10$), supporting the existence of a substantial amount of dark matter. We also confirm that M/L is not constant with radius.

These values are significantly larger than the value $M/L = 17$ determined by Bicknell et al. (1989), from the stellar velocity dispersion measurements at radii <86″. There is therefore strong evidence for a change in the character of the gravitational potential at about 2′ – 3′ from the center of NGC 1399. We conclude, as suggested by Grillmair et al. (1994), that most of the globular clusters in our sample are orbiting in a gravitational potential which is more closely associated with the galaxy *cluster* rather than with NGC 1399 itself. As the velocity dispersion profile measured for planetary nebulae at large radii is very similar to that of the globular clusters, we must conclude that the stars in the outer cD envelope are similarly associated with the potential of the Fornax cluster as a whole (see also Arnaboldi et al. 1996, Mendez et al. 1997). This would be consistent with the recent detection of red giant branch stars in the intergalactic region of the Virgo cluster (Ferguson, Tanvir, & von Hippel 1998).

Recent radial velocity measurements by Cohen & Ryzhov (1997) of globular clusters in M87 show similar velocity dispersions for stars and globular clusters within 100″ of the center of M87, but a steadily rising velocity dispersion from there outward. These authors are similarly driven to conclude that the mass-luminosity ratio increases substantially with radius. This similarity may not be surprising as M87 and NGC 1399 both occupy the center of their respective cluster potentials.

4.3. A comparison with the Fornax galaxy cluster

4.3.1. The galaxies surrounding NGC 1399

An examination of the velocity distribution of 68 Fornax galaxies studied by Ferguson (1989) using the statistical tests described in Sect. 3 reveals multiple peaks of marginal significance similar to those apparent in Figure 2. This motivated us to look for sub–structure within the Fornax cluster. We applied a Dressler & Shectman (1988) test on the entire sample of galaxies; with the exception of a group of galaxies surrounding NGC 1316 (Fornax A, located at a projected distance of $\simeq$ 1.2 Mpc SW of NGC 1399), we found no evidence for sub–structure. The Fornax cluster appears to be very homogeneous. This is in good accord with the general view that Fornax is a very compact, relatively relaxed cluster. Leaving the group around NGC 1316 out of the velocity distribution considerably diminishes the statistical significance of the double peak (to $< 50\%$).

The mean velocity of the 57 remaining galaxies in Fornax is 1459 ± 40 km s^{-1}, consistent with the systemic velocity of NGC 1399. This confirms that NGC 1399 sits at the center of the cluster potential well. The velocity dispersion of the galaxy cluster rises from $\sigma = 276$ km s^{-1} in the outer parts (several degrees from the cluster center) to $\sigma = 413$ km s^{-1} within 24′ of NGC 1399 (den Hartog & Katgert 1997). There is very good agreement (Figure 6) between the velocity dispersions of the galaxies and the globular clusters.

4.3.2. The X-ray gas

Jones et al. (1997) find that the hot X-ray gas around NGC 1399 has a temperature of 1.30 ± 0.05 keV (derived within an annulus extending from 2' to 18'). This is energetically equivalent to a velocity dispersion of $\sigma \simeq 450$ km s^{-1}. The temperature profile, converted into a velocity dispersion profile, is shown as the dashed line in Fig. 6. Once again the agreement with the globular cluster measurement is excellent. Ikebe et al. (1996) showed that the X-ray gas profile could be modeled as the sum of two components, perhaps responding to the potentials of NGC 1399 and the Fornax cluster, respectively. The potential of the galaxy evidently falls off steeply and only clearly dominates over the cluster potential in the inner 2′ to 3′. Beyond 5′ or 6′, the potential of the cluster dominates.

5. Discussion

In order to better understand the origin of the NGC 1399 globular cluster system, with its high velocity dispersion and specific frequency (number of globular clusters per unit luminosity, Harris & van den Bergh 1981), we pose the question whether the properties of these globular clusters are peculiar in any way. We briefly compare the globular cluster system of NGC 1399 with those of the next brightest early–type galaxies in Fornax, NGC 1380 and NGC 1404. We then discuss our findings within the framework of different scenarios that could explain the globular cluster over–abundance.

Note that NGC 1399 is traditionally associated with high–S_N galaxies, although Ostrov et al. (1998) recently suggested that it has only a moderate over–abundance. The new value is a consequence of taking proper account of the light in the extended cD halo. The S_N value for NGC 1399, galaxy and cD envelope is still about a factor of two higher than for other galaxies in Fornax. In particular, the S_N of the cD envelope reaches values a factor of 3 higher than the mean of the brightest surrounding ellipticals, and when the globular clusters are associated with the "galaxy" component alone, the S_N reaches values of a factor 5 to 6 higher than the Fornax mean.

In the following we will distinguish between NGC 1399 including the cD envelope, the "galaxy" component alone (to which we associate the light of a de Vaucouleurs fit to the central region), and the cD envelope. M_V and S_N for the different components are listed in Table 2.

5.1. Photometric and chemical properties of the globular clusters surrounding NGC 1399

The globular cluster system of NGC 1399 has been extensively studied photometrically (Hanes & Harris 1986, Geisler & Forte 1990, Wagner, Richtler & Hopp 1991, Bridges, Hanes & Harris 1991, Ostrov, Geisler & Forte 1993, Kissler-Patig et al. 1997a, Forbes et al. 1998, Ostrov et al. 1998, Grillmair et al. 1999). The most striking result of these investigations is the high number of globular clusters surrounding the galaxy, and the over-abundance in the number of globular clusters per unit light when compared with the other "normal" cluster ellipticals (see Table 2).

Another interesting finding of the more recent studies is that the globular cluster color distribution has at least two significant peaks, suggesting two or more sub-populations. The photometric studies found that these peaks are separated by about 1 dex in [Fe/H] and, taking into account the luminosity function, that the majority of the globular clusters are as old (within a few Gyr) as the oldest globular clusters in the Galaxy. The nature of these sub-populations was explored spectroscopically by Kissler-Patig et al. (1998). The absorption line indices for the two major sub-populations of globular clusters were found to be very similar to the ones observed in globular clusters around M31 and the Galaxy, suggesting similar formation epochs and mechanisms. Thus the majority of globular clusters around NGC 1399 appear to be "normal" old globular clusters. A small fraction of very red globular clusters are significantly more metal rich, and could perhaps have formed in a later merger.

5.2. Comparison with the globular cluster systems of NGC 1380 and NGC 1404

Do NGC 1380 and NGC 1404 have globular cluster systems comparable to that of NGC 1399? These two galaxies are the next brightest early-type galaxies in Fornax (neglecting currently star-forming NGC 1316). NGC 1380 and NGC 1404 are 1.4 and 1.5 magnitudes fainter, respectively, than the central cD galaxy, and only 0.3 and 0.4 magnitudes fainter if the light of the cD envelope is neglected (see Table 2). These galaxies are projected only 38′ (208 kpc) and 9′ (48 kpc) from NGC 1399 and are presumably well within the embrace of the Fornax cluster potential.

While no spectroscopic observations have yet been made of the globular clusters surrounding these other two galaxies, a considerable amount of photometric work has been published (NGC 1380: Kissler-Patig et al. 1997b; NGC 1404: Hanes & Harris 1986, Richtler et al. 1992, Forbes et al. 1998, Grillmair et al. 1999). Qualitatively, the globular cluster systems of NGC 1399, NGC 1404 and NGC 1380 look very similar. All three systems exhibit broad color distributions with two (or possibly three) peaks (Ostrov et al. 1993, Kissler-Patig et al. 1997a,b, Forbes et al. 1998, Grillmair et al. 1999). The ratio of red to blue globular clusters is roughly the same in all three cases, and between 1 and 2 when integrated over the whole system. Furthermore, the two main sub-populations peak at similar metallicities (as derived from broad-band colors) in the three systems. The blue populations are distributed around a metallicity typical for the Galaxy or M31 halo globular clusters, i.e., $-1.5 <$ [Fe/H] < -1.0 dex. The red populations seem to have metallicities slightly higher than disk/bulge globular clusters in the Galaxy (i.e., $-0.5 <$ [Fe/H] < -0.1 dex, cf. Minniti 1995, although the former could be slightly over-estimated from the broad-band colors, see Kissler-Patig et al. 1998).

Finally, the globular cluster luminosity functions of all three systems look similar and are well represented by a Gaussian with a 1.2 ± 0.2 mag dispersion and peak at about the same magnitude to within the errors (see Table 4). Assuming that the underlying globular cluster mass distributions are invariant, this result suggests that the globular clusters in the three galaxies have similar old ages.

The only significant difference between the globular cluster system of NGC 1399 and those of NGC 1404 and NGC 1380 is the much higher number of clusters around NGC 1399. Quantitatively, NGC 1399 is surrounded by 5800 ± 300 globular clusters, while NGC 1404 and NGC 1380 host only 800 ± 100 and 560 ± 30 globular clusters respectively (see Table 2). In terms of specific frequency, NGC 1399 has $S_N = 4.1 \pm 0.6$ ($S_N = 11 \pm 1$ for the "galaxy" component) NGC 1404 has $S_N = 2.3 \pm 0.3$, and NGC 1380 has $S_N = 1.5 \pm 0.2$. Using the distance in Table 2 and the magnitudes and colors of the galaxies from the RC3, the four smaller early-type galaxies in Fornax NGC 1387, NGC 1374, NGC 1379, NGC 1427 (Kissler-Patig et al. 1997a) have specific frequencies between 2.1 and 3.2 with a mean of 2.6 ± 0.6 (where the error is the dispersion around the mean). NGC 1399, or rather the center of the Fornax cluster, is outstanding in its relative overabundance of globular clusters, while NGC 1404 and NGC 1380 have cluster populations close to the mean expected value.

In summary, the globular clusters around NGC 1399 are qualitatively very similar to the ones surrounding NGC 1380 and NGC 1404, and appear "normal" when compared to the globular clusters of the Galaxy. However, the central galaxy hosts a factor 10 more globular clusters than its neighbors and has a specific frequency 2 to 3 times higher than expected. Based on all the evidence summarized above, we are led to two conclusions: *i)* the excess globular clusters do not have unusual properties, i.e., they are likely to have formed in the same kind of process and at a similar time as the globular clusters in NGC 1404 and NGC 1380, and *ii)* the excess number of globular clusters is most likely linked to the special location of NGC 1399 in the center of the cluster.

5.3. Constraints on scenarios explaining the high specific frequencies around central giant ellipticals

5.3.1. Current scenarios

Various scenarios to explain the high S_N values around central galaxies have been comprehensively discussed by Blakeslee et al. (1997). These authors found several correlations of specific frequency with the galaxy cluster properties, including X-ray temperature, velocity dispersion, and galaxy distance from the center of the cluster. In summary, *ab initio* scenarios (Harris 1991 and references therein) that associate the excess numbers of globular clusters to super-efficient globular cluster formation in these galaxies fail to explain the correlation of S_N, cluster X-ray properties and velocity dispersion. Mergers as a source of the increase in S_N (e.g. Ashman & Zepf 1992) also fail to explain these correlations and have difficulty explaining the ratio of blue and red globular clusters if the red globulars are thought to be responsible for the high S_N values (Forbes, Brodie & Grillmair 1997).

Scenarios which involve biased formation of globular clusters in deep potential wells (West 1993) and intra-cluster globular clusters (West et al. 1995) are largely unconstrained, and Blakeslee et al. cannot rule them out. Tidal stripping can easily explain all of their observed correlations; the problem, as noted by Blakeslee et al., is that the stripping simulations (summarized in Muzzio 1987) yield too slow an increase in S_N of the central galaxy. Finally, motivated by the constant luminosity of Brightest Cluster Galaxies (BCGs), Blakeslee et al. propose a new scenario wherein globular clusters formed early and their numbers scaled with the available mass in the galaxy cluster, whereas the luminosity of the BCGs is relatively independent of the cluster mass and is truncated at a given luminosity. The upshot is that abnormally high S_N values would be interpreted as a *luminosity deficiency* rather than a globular cluster over-abundance (see also Harris et al. (1998) for further support to this idea).

Based on the observations presented above, we concur that excessive numbers of globular clusters are likely to be linked to the properties (X-ray temperature; velocity dispersion) of the galaxy cluster and the special location of high-S_N galaxies.

5.3.2. Constraints from the properties of the excess globular clusters

Any scenario that purports to explain the excess of globular clusters around NGC 1399 must be consistent with the finding that their properties are very similar to those of globular clusters in NGC 1404 and NGC 1380. As discussed above, several sub-populations have been identified in NGC 1399. The two major ones, making up over 90% of the system, are old and have mean metallicities of [Fe/H]$\simeq -1.3$ and $\simeq -0.6$ dex respectively. The ratio of these two populations changes slowly with radius, varying from about 2:1 (red/blue) in the center of the galaxy to about 1:2 in the cD halo, with an overall average close to 1:1 (see Kissler-Patig et al. 1997a and Forbes et al. 1998). In principal, the excess globular clusters could be made up by metal-rich or metal-poor globular clusters only. Both cases would be inconsistent with NGC 1404 and NGC 1380 having also metal-poor *and* metal-rich clusters, but showing no over-abundance. This suggests that the excess of globular clusters (especially around the "galaxy" component) must be made up of both old, metal-poor *and* old, metal-rich clusters.

This complicates scenarios wherein all the excess clusters are formed at a very early stage, before the galaxies fully assembled (i.e., West et al. 1993; Blakeslee et al. 1997; Harris et al. 1998). Such scenarios would require that NGC 1399 have a specific frequency about a factor of two higher than normal, but that all of the extra clusters be metal-poor. A mechanism that can explain at least some increase in the number of red globular clusters seems required.

5.3.3. *Constraints from the properties of BCGs*

Recent work by Aragón-Salamanca et al. (1997) puts further constraints on scenarios which require an excess number of globular clusters to have formed at very early times. These authors see no (or negative) passive evolution in the K-band Hubble diagram of BCGs. Furthermore, they detect no young stellar populations. They conclude that the total mass of stars in BCGs has grown by a factor of 2 (4) since $z = 1$ for $q_0 = 0$ ($q_0 = 0.5$), and cannot be explained by new stars forming in mergers or cooling flows. BCGs must therefore have accreted or annexed mass in the form of old stars (and presumably old globular clusters) since $z = 1$; either by cannibalism — accreting gas-poor galaxies — or by stripping of material from other galaxies.

5.3.4. *Constraints from the high specific frequency*

Irrespective of the high *total number* of globular clusters, the high specific frequency, when compared to the neighbor galaxies, also needs to be taken into account. If NGC 1399 gained mass simply by dissipationless mergers of typical galaxies surrounding it, then the specific frequency would *decrease* (by about 30% for each doubling of the mass for NGC 1399), since no neighboring galaxy has a S_N value much higher than 3. Dissipationless merging therefore seems unlikely to be the main cause for the growth of the central galaxy since $z = 1$, unless the specific frequency of NGC 1399 was even higher at early times. We would then need an explanation for the original, even higher, specific frequency. It seems to us more reasonable to suppose that the mass gained by NGC 1399 consisted of accreted material with an intrinsically high specific frequency of globular clusters that matches the $S_N \simeq 6$ of the cD halo (see table 2).

Potential accretion candidates with high specific frequencies include faint dwarf galaxies and galactic halos. Durrel et al. (1996) compiled a table of S_N values for local group dwarfs and several dwarf ellipticals in Virgo. They find that dE galaxies with $M_V < -15.5$ tend to have a "normal" specific frequency (4.2 ± 1.8), whereas their two faintest dE,N galaxies have very high S_N values (15 ± 8 and 12 ± 9 respectively). At least two other, local group, low-luminosity dwarf galaxies are also known to exhibit very high values: Fornax (29 ± 6) and Sagittarius (25 ± 9). Miller et al. (1998) recently enlarged the sample of dE galaxies with studied globular cluster systems by 24 and extended Durrel et al.'s results in the sense that their dE,N galaxies with $M_V < -15.5$ also have S_N values around 10 or above. However, brighter and non-nucleated dEs appear to have more normal specific frequencies. Simulations by Côté et al. (1998) indicate that the accretion/stripping of a large number of dwarf galaxies could explain the color distributions seen around giant ellipticals, assuming that every individual galaxy forms globular clusters with a mean metallicity proportional to its size. However, the presence of a large number of such nucleated dwarf galaxies remnants at the current epoch around NGC 1399 can be ruled out (Hilker 1998 (chapter 5), Hilker et al. 1998a,b and references therein). Hilker (1998) further showed in Monte-Carlo simulations that dwarf galaxies (or their halos) cannot explain all the excess of globular clusters around NGC 1399, even if one assumes an extremely steep faint-end of the galaxy luminosity function in the past and efficiently accrete all the dwarf galaxies "missing" in todays luminosity function onto NGC 1399. Therefore, while accretion of dwarf galaxies may have played a role in the enrichment of the globular cluster system of the central galaxy, it cannot be its only cause.

Another source of high specific frequency material may be galactic "halos". Extended globular cluster systems often fall off more slowly with radius than the stellar light profile, leading to gradually increasing specific frequencies in the outskirts of the distributions. Recent studies have identified distinct "halo" globular cluster populations in early-type galaxies (Kissler-Patig et al. 1997b; Lee, Kim & Geisler 1998) comprised of clusters following a somewhat shallower density profile. M87 is a clear case, for which McLaughlin et al. (1994) computed an increase of S_N from values around 10 inside 1 $r_{\rm eff}$ to 25 at >5 $r_{\rm eff}$. Unfortunately, such studies do not yet exist for isolated field galaxies, but "halo" material can be considered a plausible candidate for the buildup of the envelope of NGC 1399 (see also Kissler-Patig 1997a and Forbes, Brodie, & Grillmair 1997). We note in passing that, in the galaxy formation models of the Searle & Zinn (1978) type, halos are built up of fragments resembling faint dwarf galaxies.

5.4. Globular cluster stripping

Several authors have investigated the importance of stripping and harassment for the formation of central cD galaxies (see e.g., Dressler 1984 for an early review). Following these ideas, Harris (1986) suggested that the central regions of galaxy clusters could have accumulated globular clusters stripped from their parent galaxies. White (1987) suggested that these clusters could have built up the over-abundant globular cluster systems around cD galaxies. Muzzio (1987) summarized the results of various simulations of globular cluster stripping in galaxy clusters. Some of his conclusions were: *i)* stripping of globular clusters was most efficient before the galaxies and cluster were virialized, *ii)* the initial extent of the halos is not critical, *iii)* the location in the cluster and the amount of dark matter determine the number of encounters and the amount of stripping a galaxy suffers, and *iv)* the brightest galaxies tend to gain globular clusters, but capture most of these from galaxies only somewhat fainter than themselves. Intermediate luminosity galaxies are the ones which lose their globular clusters; faint or dwarf galaxies are hardly affected. Unfortunately, the exact properties of the resulting globular cluster systems depend too much on the initial conditions and the details of the simulations (which had rather poor resolution) to allow detailed predictions. We discuss the plausibility of the "stripping" scenario in more detail below.

5.4.1. Do the numbers work out?

We first determine whether the total number of globular clusters seen in the early-type galaxies in Fornax requires that an additional formation process be invoked, or if it can be explained by a simple redistribution of existing clusters. In other words, do the galaxies in the cluster form a reservoir of globular clusters large enough to feed the central galaxy? To answer this question, we assume that all galaxies had the same number of globular clusters per unit luminosity to begin with, and that the excess around NGC 1399 must be accounted for by the losses suffered by other galaxies. What, then, was the initial "universal" specific frequency in Fornax?

Table 5 summarizes the result. It shows the number of globular clusters observed today in each of brightest early-type galaxies in the center of the Fornax cluster, the number of globular clusters initially resident in each galaxy for an assumed "universal" specific frequency, and the number which had to be gained or lost. Assuming an initial $S_N = 3.2$ for NGC 1399, NGC 1404, NGC 1380, NGC 1374, NGC 1379, NGC 1387, and NGC 1427, one can account for all the globular clusters seen in these galaxies today. If we assume that the next seven brightest early-type galaxies (NGC 1336, NGC 1339, NGC 1351, IC 1963, NGC 1380A, NGC 1381, NGC 1389, taken from Ferguson 1989), all with total magnitudes brighter than $M_V \simeq -19$, suffered the same losses as the other non-central galaxies, the initial specific frequency could have been as low as 3. Note that the largest losses were suffered by the brightest galaxies. Including contributions from dwarf galaxies could lower the required initial mean value of S_N still further.

Even if all globular clusters were associated with the "galaxy" component, and todays S_N value for NGC 1399 was taken to be >10, a similar calculation would lead to an initial S_N of $\simeq 4$ for all Fornax galaxies.

S_N values of 3 to 4 are not unusual among early-type, cluster ellipticals. The mean for all early-type galaxies with $-19.0 < M_V < -21.4$ in various compilations is $S_N = 3.7 \pm 3.1$ (Harris 1991), $S_N = 4.1 \pm 2.9$ (Ashman & Zepf 1998) and $S_N = 4.6 \pm 2.7$ (Kissler-Patig 1997b), where the quoted error is the dispersion about the mean. *However*, these numbers need to be confirmed for a sample of isolated field ellipticals with absolute magnitude $-19 < M_V < -22$ before we can say with confidence that this is likely to be representative of cluster ellipticals prior to any interactions. Nonetheless, the point we wish to stress is that *the excess population around the central galaxy in Fornax does not require the production of a large number of new globular clusters.* A simple redistribution, separating globular clusters from their parent galaxies through tidal encounters, is sufficient to account for the observations. NGC 1399 (or perhaps more correctly the central potential of the Fornax cluster) would have gained about 65% of its current light (assuming for the galaxy without envelope $M_V = -21.76$, see Table 2), and 75% of its current globular clusters through stripping and harassment. NGC 1380 and NGC 1404 would have lost 30% to 50% of their globular clusters, and all other intermediate-size galaxies would have lost between 0% and 30% of their initial globular cluster populations.

In the above, we neglected the possible existence of a population of intra-cluster globular clusters (West et al. 1995, Blakeslee 1996) which was *never* associated with a cluster galaxy. If indeed such globular clusters formed at early times, then the numbers of globulars removed from cluster galaxies needs to be even less, and the initial specific frequency could be even lower than the values we have estimated above. However, little is yet known concerning such a population, making any estimate of its importance uncertain.

Mergers, both gas-rich and gas-poor, must presumably have occurred during the evolution of the Fornax cluster. However, rather than increasing the specific frequency as has been often suggested (e.g., Zepf & Ashman 1993), such mergers could just as easily conserve S_N (e.g., van den Bergh 1995).

5.4.2. Are the other properties of the globular cluster systems compatible with stripping?

Kissler-Patig et al. (1997a) showed that the combined color distribution of globular clusters in the intermediate luminosity galaxies surrounding the central galaxy (NGC 1374, NGC 1379, NGC 1387, and NGC 1427) is also consistent with the observed color distribution in NGC 1399, and that this is compatible with the stripping scenario.

Unfortunately, as noted above, few simulations of the stripping of globular clusters in galaxy clusters exist. Muzzio (1987) summarized a number of simulations but was unfortunately not able to make clear predictions. Globular cluster systems are expected to become extended in response to the tidal stresses imposed by neighboring galaxies. However, it is not clear whether by this time we should expect to see surface density profiles which are tidally truncated, or whether they should appear extended. Tidal encounters will naturally lead to the growth of tidal tails and to the possible destruction of numerous globular clusters (Gnedin & Ostriker 1997, Combes et al. 1998). The onset of such tidal tails may be detectable in the form of a "break" in the surface density profile (Grillmair et al. 1995; 1999).

5.4.3. A possible scenario

Currently available information on the globular cluster system of NGC 1399 seems to favor the view that its high specific frequency mainly results from tidal stripping of relatively high-S_N material from neighboring galaxies. If this is the case for other nearby central cluster galaxies, it would explain the correlations of S_N with galaxy cluster properties (Blakeslee et al. 1997). In the case of NGC 1399, stripping is consistent with all known properties of the globular cluster system, including the total number of globular clusters in the cluster galaxies. While this seems sensible, detailed simulations will be needed to check this suggestion. A potential remaining problem, as already pointed out by Blakeslee et al. 1997, is the inefficiency of stripping once galaxy clusters are virialized. This apparent problem would however be resolved if a significant fraction of the tidal stripping occurred during the early phases of galaxy formation, when the halos of galaxies first collapsed and the old, metal-poor globular cluster population formed. However, tidal effects would continue to pull clusters from their host galaxies until the present day, although at reduced efficiency. This, as well as dissipative post-collapse merger events, would allow for the addition of more metal-rich globulars to the mix. All the constraints discussed in the above sections would remain satisfied.

6. Summary and conclusions

We have combined data from three separate spectroscopic investigations to study the kinematics of 74 globular clusters around NGC 1399. The velocity dispersion of the globular clusters increases with radius, rising from a value not unlike that for the outermost stellar measurements at 2 $r_{\rm eff}$, to values almost twice as high at >5 $r_{\rm eff}$. The outer velocity dispersion measurements are in good agreement with the temperature of the X-ray gas and the velocity dispersion of galaxies in the Fornax cluster. We conclude, as already suggested by Grillmair et al. (1994), that a large fraction of the globular clusters which we associate with NGC 1399 should rather be attributed to the whole of the Fornax cluster. No significant difference in the kinematics could be found between the blue and red globular cluster sub-populations, but there is some evidence for rotation in the outer ($> 5'$) regions.

A qualitative comparison of the globular cluster systems of NGC 1399 and neighboring, next-brightest early-type galaxies NGC 1404 and NGC 1380 indicates that these systems are indistinguishable from one another, and that there is no reason to suppose that they formed at significantly different epochs or via a different sequence of events. The NGC 1399 globular cluster system is distinguished only in being a factor of 10 more abundant than the cluster systems of either of the other two galaxies, and having a specific frequency 2 to 3 times higher. The excess is best understood if a significant fraction of the globular clusters is indeed associated with the light of the cD envelope. By association this would mean that the cD envelope around NGC 1399 should rather also be associated with the Fornax cluster than with the galaxy itself.

We review different scenarios to explain the high specific frequencies around the central galaxies and examine the consequences of various existing constraints for each. We come to the conclusion that tidal stripping of globular clusters from neighboring galaxies in the early history of the galaxy cluster and the consequent buildup of the cD envelope in the Fornax cluster potential well is the most likely explanation.

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TABLE 1

GLOBULAR CLUSTERS AROUND NGC 1399 WITH MEASURED RADIAL VELOCITIES

ID	RA(1950)	DEC(1950)	$v_{\rm helio}$	V ± 0.02	$V-I$ ± 0.035	B_j $\pm \simeq 0.2$	$B_j - R$ $\pm \simeq 0.3$	other $v_{\rm helio}$
aat 1	3 35 47.3	−35 40 21	1121 ± 150	...	...	21.7	1.31	
aat 4	3 35 49.2	−35 36 44	2478 ± 150	...	...	22.3	1.04	
aat 5	3 35 50.1	−35 38 48	1624 ± 150	...	...	21.3	1.32	
aat 6	3 35 51.4	−35 37 52	1186 ± 150	...	...	21.9	1.13	
aat 7	3 35 52.0	−35 32 44	1385 ± 150	...	...	21.5	0.98	
aat 8	3 35 54.8	−35 38 09	1152 ± 150	...	...	22.4	0.84	
aat 10	3 35 58.4	−35 36 03	1068 ± 150	...	...	21.9	0.91	
aat 13	3 36 03.6	−35 31 58	1922 ± 150	21.15	0.97	21.9	1.05	
aat 15	3 36 05.2	−35 39 54	1355 ± 150	...	...	21.9	1.05	
aat 16	3 36 05.9	−35 34 20	1766 ± 150	21.27	1.17	22.1	1.16	
aat 17	3 36 07.8	−35 34 44	1784 ± 150	21.57	0.92	22.3	0.89	
aat 20	3 36 17.8	−35 38 42	1836 ± 150	...	...	21.6	1.33	
aat 21	3 36 18.2	−35 40 52	2085 ± 150	...	...	21.9	1.27	
aat 25	3 36 22.7	−35 38 12	2182 ± 150	...	...	22.4	1.19	
aat 26	3 36 23.5	−35 37 25	1646 ± 150	20.80	1.06	21.8	1.54	
aat 27	3 36 14.7	−35 33 54	1921 ± 150	21.85	0.96	22.3	0.81	
aat 30	3 36 24.2	−35 42 07	1859 ± 150	...	...	21.8	1.05	
aat 31	3 36 24.7	−35 33 24	1236 ± 150	20.59	1.01	21.4	1.23	
aat 33	3 36 30.1	−35 39 10	1350 ± 150	...	...	21.6	1.48	
aat 34	3 36 35.1	−35 31 15	1701 ± 150	20.78	1.01	21.6	1.17	
aat 36	3 36 41.3	−35 41 56	1038 ± 150	21.97	1.43	22.3	1.17	
aat 38	3 36 43.0	−35 33 16	574 ± 150	20.85	1.18	21.7	1.40	
aat 39	3 36 44.5	−35 38 31	1639 ± 150	21.19	1.27	22.0	1.32	
aat 40	3 36 44.4	−35 36 49	1539 ± 150	20.78	1.21	21.8	1.54	
aat 41	3 36 45.7	−35 38 53	571 ± 150	20.93	1.22	21.7	1.31	
aat 42	3 36 45.8	−35 37 33	1504 ± 150	20.74	1.42	21.5	1.69	
aat 43	3 36 46.0	−35 32 26	1623 ± 150	21.23	1.13	21.9	1.17	
aat 48	3 36 52.4	−35 34 33	885 ± 150	21.71	1.16	22.4	1.19	
aat 49	3 36 46.9	−35 35 44	2026 ± 150	21.30	1.28	22.2	1.55	
aat 54	3 36 51.9	−35 33 32	1941 ± 150	21.04	0.97	21.9	1.29	
aat 55	3 36 54.0	−35 37 27	1821 ± 150	20.94	1.00	21.6	1.01	
aat 56	3 36 54.1	−35 31 25	1206 ± 150	21.39	1.15	21.7	1.29	
aat 57	3 36 55.4	−35 31 51	1742 ± 150	20.91	1.12	22.2	1.26	
aat 59	3 36 59.9	−35 41 21	1862 ± 150	21.12	0.75	21.5	1.24	
aat 62	3 37 01.2	−35 40 49	794 ± 150	21.25	0.89	21.2	1.35	
aat 66	3 37 10.1	−35 36 36	845 ± 150	21.17	1.12	21.8	0.98	
aat 67	3 37 10.8	−35 38 42	1343 ± 150	21.61	0.83	22.3	1.09	
aat 68	3 37 14.3	−35 37 11	1166 ± 150	...	...	21.6	1.18	
aat 69	3 37 15.1	−35 33 46	1938 ± 150	...	...	22.4	0.97	
aat 71	3 37 21.5	−35 39 41	1843 ± 150	...	...	22.4	1.06	
ntt 201	3 36 44.2	−35 35 40	1061 ± 135	21.17	1.24	...	...	
ntt 203	3 37 02.9	−35 34 40	994 ± 073	20.69	1.08	...	...	
ntt 208	3 36 55.0	−35 31 31	1275 ± 091	20.91	1.12	...	...	
ntt 407	3 36 09.8	−35 35 02	2107 ± 159	20.19	1.01	...	...	

TABLE 1—*Continued*

ID	RA(1950)	DEC(1950)	$v_{\rm helio}$	V ±0.02	$V-I$ ±0.035	B_j $\pm\simeq0.2$	B_j-R $\pm\simeq0.3$	other $v_{\rm helio}$
ntt 410	3 36 17.7	−35 33 45	1190 ± 094	19.83	1.27	...	...	
ntt 414	3 36 15.5	−35 32 40	1565 ± 105	19.56	1.09	...	...	
ntt 101	3 36 55.4	−35 44 05	1270 ± 118	...	...	...	...	
ntt 109	3 36 58.9	−35 41 46	1426 ± 120	21.24	1.27	...	...	1249 ± 103 , aat 58 $1801\pm$
ntt 113	3 36 40.7	−35 40 46	1440 ± 138	21.15	1.26	...	...	
ntt 119	3 37 01.7	−35 38 18	1327 ± 121	21.16	1.19	...	...	1349 ± 105, aat 63 1282 ± 1
ntt 122	3 37 03.5	−35 37 43	1731 ± 092	20.77	1.06	...	...	
ntt 123	3 36 54.1	−35 37 32	1307 ± 164	20.93	1.00	...	...	
ntt 124	3 36 43.0	−35 37 14	1142 ± 189	21.18	1.25	...	...	
ntt 125	3 36 41.0	−35 37 00	1772 ± 142	21.02	1.17	...	...	
ntt 126	3 36 44.7	−35 36 52	723 ± 207	20.76	1.22	...	...	
ntt 127	3 36 43.5	−35 36 32	1811 ± 095	21.06	1.16	...	...	
keck 1	3 36 13.8	−35 39 24.8	732 ± 032	...	...	21.8	...	
keck 2	3 36 14.2	−35 38 51.2	1094 ± 034	...	...	22.4	1.19	
keck 3	3 36 09.4	−35 37 32.4	1571 ± 031	...	...	22.3	1.02	
keck 5	3 36 13.2	−35 37 37.8	1775 ± 066	...	...	21.8	1.17	
keck 6	3 36 17.8	−35 37 50.2	1386 ± 031	...	...	22.3	...	
keck 7	3 36 16.7	−35 37 01.7	1448 ± 103	21.01	1.23	21.7	1.31	1376 ± 84, aat 28 1677 ± 15
keck 9	3 36 19.2	−35 36 28.7	1155 ± 042	21.04	1.25	21.8	1.33	1150 ± 31, aat 29 1280 ± 15
keck 10	3 36 21.5	−35 36 04.4	843 ± 045	20.55	1.05	21.4	1.50	815 ± 30, ntt 406 917 ± 55,
keck 11	3 36 25.0	−35 36 28.3	1338 ± 033	21.34	1.17	22.2	1.50	
keck 12	3 36 20.3	−35 35 15.3	1734 ± 042	21.97	0.94	22.4	1.06	1736 ± 31, aat 23 1701 ± 15
keck 13	3 36 23.4	−35 35 37.2	1247 ± 030	21.51	0.91	22.2	...	
keck 14	3 36 24.5	−35 35 36.8	1260 ± 066	21.17	1.37	22.1	1.65	
keck 15	3 36 23.2	−35 34 39.3	1523 ± 030	21.26	1.04	22.0	1.26	
keck 17	3 36 26.3	−35 34 20.7	866 ± 071	21.55	1.14	22.4	1.33	
keck 18	3 36 31.4	−35 35 05.9	1688 ± 042	21.32	1.08	22.3	1.50	
keck 19	3 36 34.5	−35 34 52.2	1150 ± 059	21.41	1.29	22.3	...	
keck 20	3 36 28.5	−35 33 17.0	1374 ± 126	21.63	1.13	22.3	0.88	
keck 21	3 36 35.7	−35 34 24.6	1154 ± 117	21.15	1.09	22.0	1.37	1194 ± 98, aat 35 1062 ± 15

The AAT data were taken from Grillmair 1992, the NTT data from Minniti et al. 1998, and the Keck data from Kissler-Patig et al. 1998. We used the original ID numbers, preceded with aat/ntt/keck respectively. The weighted mean velocity was computed when multiple measurements were available, the original measurements and cross references are given in the last column. V and $V-I$ were taken from Kissler-Patig et al. 1997a, B_j and B_j-R were taken from Grillmair 1992.

TABLE 2
PROPERTIES OF THE GALAXIES NGC 1399, NGC 1404, AND NGC 1380

	NGC 1399	NGC 1404	NGC 1380	Reference
RA (1950)	03 36 34.0	03 36 57.0	03 34 31.0	RC3
DEC (1950)	−35 36 42	−35 45 18	−35 08 24	RC3
l	236.71	236.95	235.93	RC3
b	−53.64	−53.56	−54.06	RC3
Type (T)	−5.0	−5.0	−2.0	RC3
$v_{\rm helio}$ km s^{-1}	1447 ± 12	1929 ± 14	1841 ± 15	RC3
$(m - M)$	31.35 ± 0.16	31.35 ± 0.16	31.35 ± 0.16	Della Valle et al. 1998[a]
V_T (mag)	8.48 ± 0.08[b]	10.00 ± 0.13	9.93 ± 0.10	Ostrov et al. 1998, RC3
M_V (mag)	-22.87 ± 0.18	-21.35 ± 0.20	-21.42 ± 0.19	using $(m - M)$ above
$(B - V)_T$ (mag)	0.96 ± 0.01	0.97 ± 0.01	0.94 ± 0.01	RC3
$(V - I)_T$ (mag)	1.23 ± 0.005	1.23 ± 0.008	1.18 ± 0.004	Buta & Williams 1995
$R_{\rm eff}$	44.7″	28.5″	...	Goudfrooij et al. 1994
N_{GC}	5800 ± 300	800 ± 100	560 ± 30	KP97a,F97,R92,KP97b
S_N	4.1 ± 0.6	2.3 ± 0.3	1.5 ± 0.2	derived from this table
S_N(halo)	6.0 ± 1.2	...	...	Ostrov et al. 1998[b]
S_N(galaxy)	11 ± 1[b]	...	...	

RC3: de Vaucouleurs et al. (1991); KP97a,b: Kissler-Patig et al. 1997a,b; F97: Forbes et al. 1998; R92: Richtler et al. 1992

[a]The distance modulus was derived for NGC 1380 and is assumed to be the same for NGC 1399 and NGC 1404. It corresponds to a distance of 18.6 Mpc

[b]Note that for NGC 1399, this includes the cD envelope. A rough estimate of the "galaxy" component can be obtained using the older value extrapolated from a de Vaucouleurs fit to the inner regions: $V_T = 9.59 \pm 0.08$ and $M_V = -21.76 \pm 0.19$, leading to $S_N = 11 \pm 1$ if all globular clusters were associated with the galaxy component.

[c]Using our assumed distance modulus, computed for a annulus with $150'' < radius < 240''$.

TABLE 3
MEAN VELOCITY AND VELOCITY DISPERSION FOR VARIOUS SAMPLES

Mean velocity	Standard Deviation	Velocity dispersion (mean fixed)	Comment
1518 ± 91	388 ± 54	...	AAT sample [a]
1353 ± 79	338 ± 56	...	NTT sample [b]
1293 ± 71	302 ± 51	...	Keck sample [c]
1429 ± 45	373 ± 35	...	Full sample
1484 ± 128	256 ± 86	263 ± 92	6 globular clusters within 2′
1393 ± 84	355 ± 63	357 ± 64	20 globular clusters within 3′
1378 ± 64	371 ± 46	375 ± 47	41 globular clusters within 5′
1498 ± 68	362 ± 52	368 ± 54	33 globular clusters outside 5′
1421 ± 83	371 ± 63	372 ± 63	23 globular clusters outside 6′
1515 ± 134	399 ± 101	408 ± 107	10 globular clusters outside 8′
1611 ± 87	313 ± 69	362 ± 104	16 blue globular clusters (V−I< 1.05)
1322 ± 58	323 ± 45	341 ± 51	36 red globular clusters (V−I> 1.05)
1356 ± 90	274 ± 71	284 ± 77	11 red globular clusters outside 5 arcmin
1643 ± 154	381 ± 117	437 ± 174	7 blue globular clusters outside 5 arcmin

Taken from [a] Grillmair et al. (1994), [b] Minniti et al. (1997), [c] Kissler-Patig et al. (1998)

[d] The dispersion was calculated around the fixed mean of the full sample (1429 km s^{-1})

TABLE 4

PEAK MAGNITUDES OF THE GLOBULAR CLUSTER LUMINOSITY FUNCTION

Galaxy	m_V (peak)	Reference
NGC 1404	24.1 ±0.2	Richtler et al. 1992
	23.92 ±0.20	Blakeslee & Tonry 1996
	24.01 ±0.20[a]	Grillmair et al. 1999
NGC 1380	24.05 ±0.25[b]	Blakeslee & Tonry 1996
	23.68 ±0.11	Della Valle et al. 1998
NGC 1399	23.90 ±0.09	Kohle et al. 1996
	23.83 ±0.15	Blakeslee & Tonry 1996
	23.85 ±0.30	Bridges et al. 1991
	23.45 ±0.16[c]	Geisler & Forte 1990
	24.0 ±0.2	Madjesky & Bender 1990
	23.73 ±0.08[a]	Grillmair et al. 1999
	23.71 ±0.12[d]	Ostrov et al. 1998

[a] Measured on V data, obtained by transforming B measurements into V using $(B-I)$ colors. [b] But see comments in Della Valle et al. 1998, [c] Converted by Geisler & Forte using $V - T_1 = 0.45$, [d] Converted from m_{T_1}(peak) assuming $(V - T_1)_0 = 0.47$.

TABLE 5

TOTAL NUMBER OF GLOBULAR CLUSTERS IN FORNAX GALAXIES

Galaxy	present N_{GC}	initial N_{GC}	# gained
Initial $S_N = 3.2$			
NGC 1399	5800	4527	1273
NGC 1380	560	1195	-634
NGC 1404	800	1113	-313
NGC 1427	510	510	0
NGC 1379	310	472	-162
NGC 1387	390	594	-204
NGC 1374	410	410	0
total	8780	8821	-41

Assumed distance to Fornax: $(m - M) = 31.35$. Galaxy luminosities taken from the RC3 to compute the S_N.
The present number of globular clusters are taken from Table 2 and Kissler-Patig et al. 1997a. Column 3 shows what must have been the initial number of globular clusters for the assumed initial S_N, Column 4 shows the difference between the initial number and the number of globular clusters presently observed.

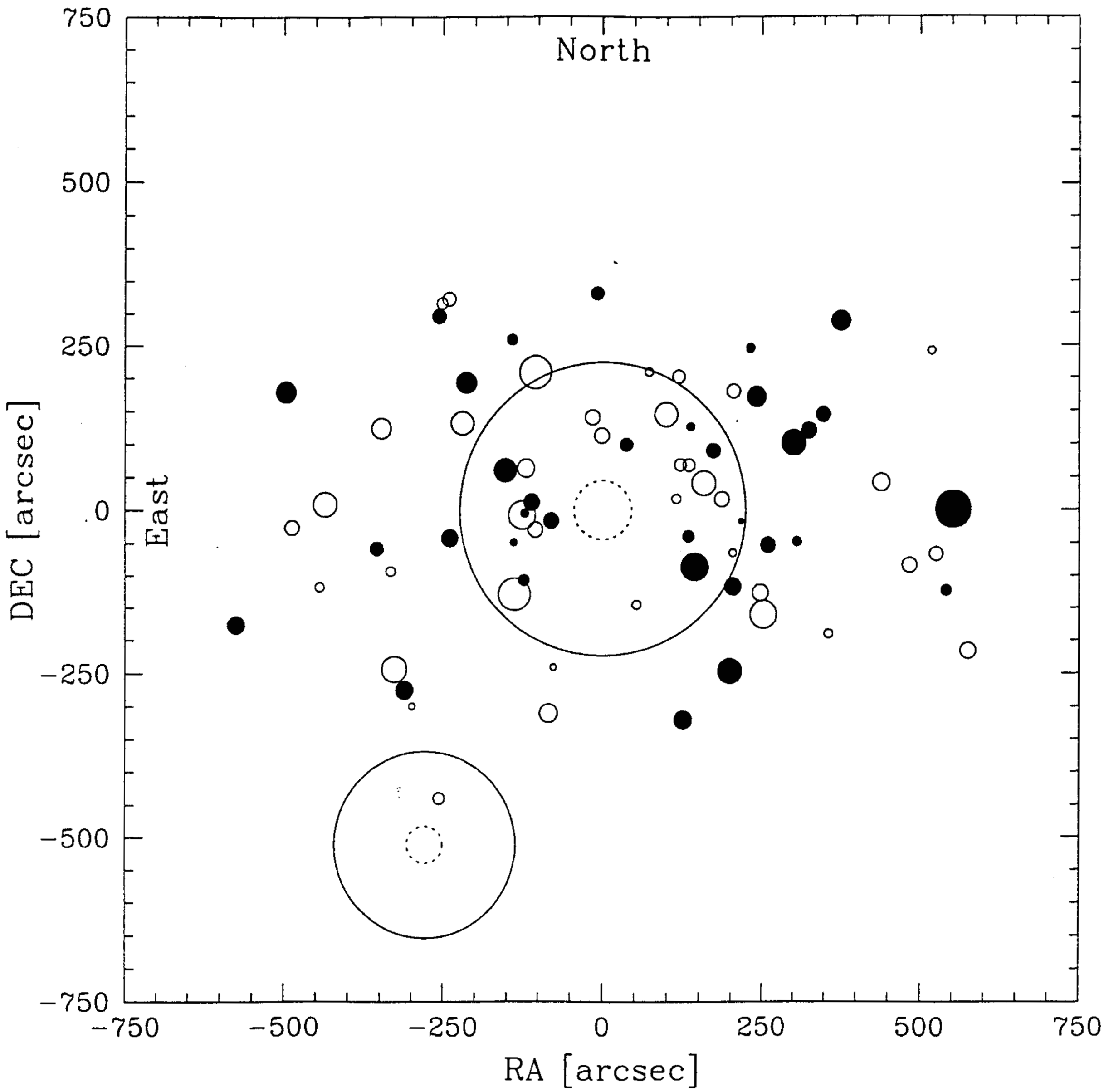

Fig. 1.— Positions of the 74 globular clusters with respect to NGC 1399 and NGC 1404. For both galaxies we indicate 1 and 5 r_{eff}. The symbols represent the globular cluster velocities: open symbols are approaching, filled symbols receding, with the size proportional to the difference between the globular cluster velocity and the mean systemic velocity of NGC 1399.

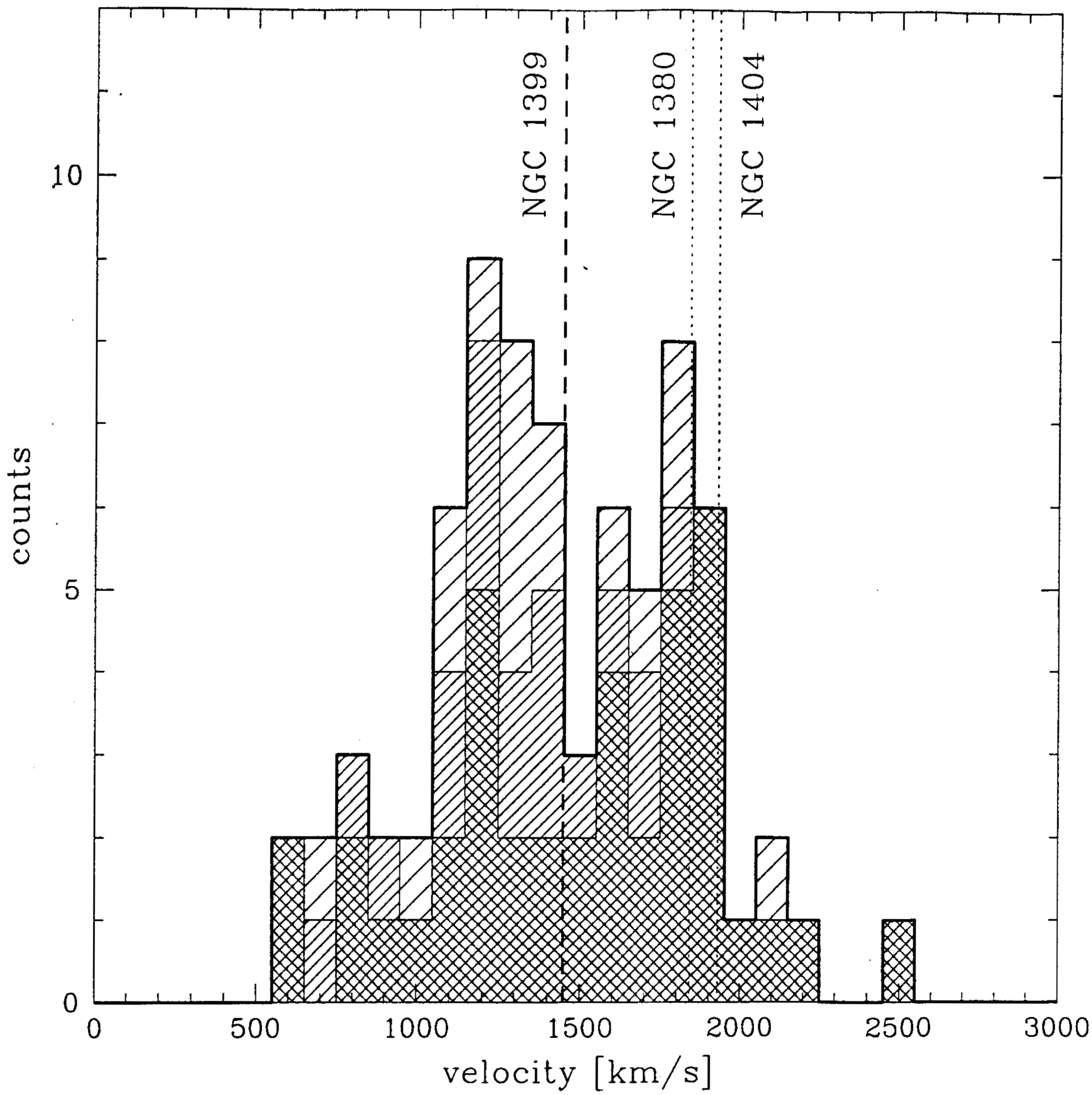

Fig. 2.— Histogram of 74 globular cluster velocity distribution. The long dashed line indicates the systemic velocity of NGC 1399, the short dashed lines the velocities of NGC 1380 and NGC 1404. The relative contributions of the AAT sample (crossed regions), the NTT sample (narrow hatched regions) and the Keck sample (hatched regions) are also shown.

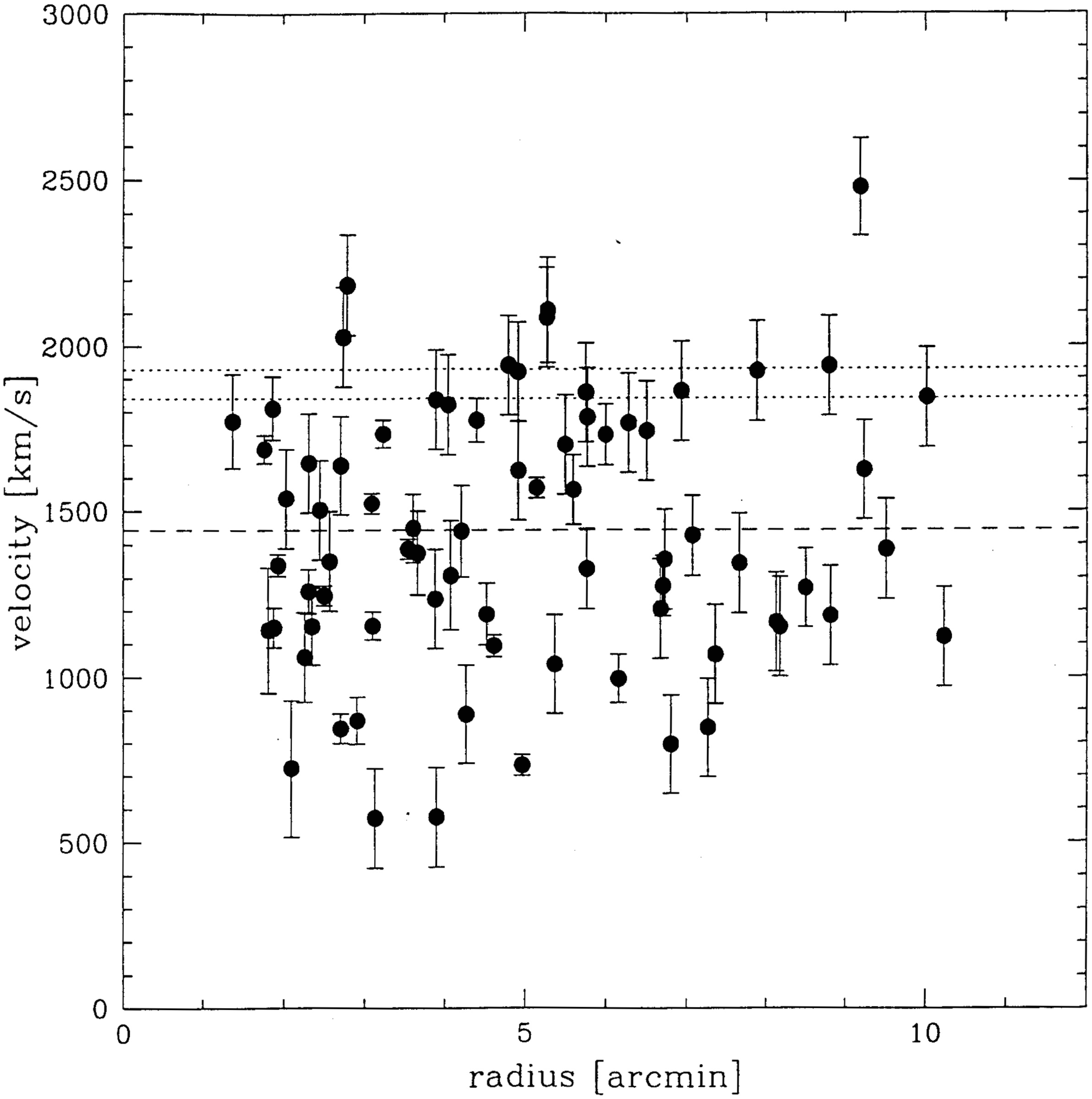

Fig. 3.— The radial velocity of the 74 globular clusters is plotted against their radius from the center of NGC 1399. The long dashed line indicates the systemic velocity of NGC 1399, the short dashed lines the velocities of NGC 1380 and NGC 1404.

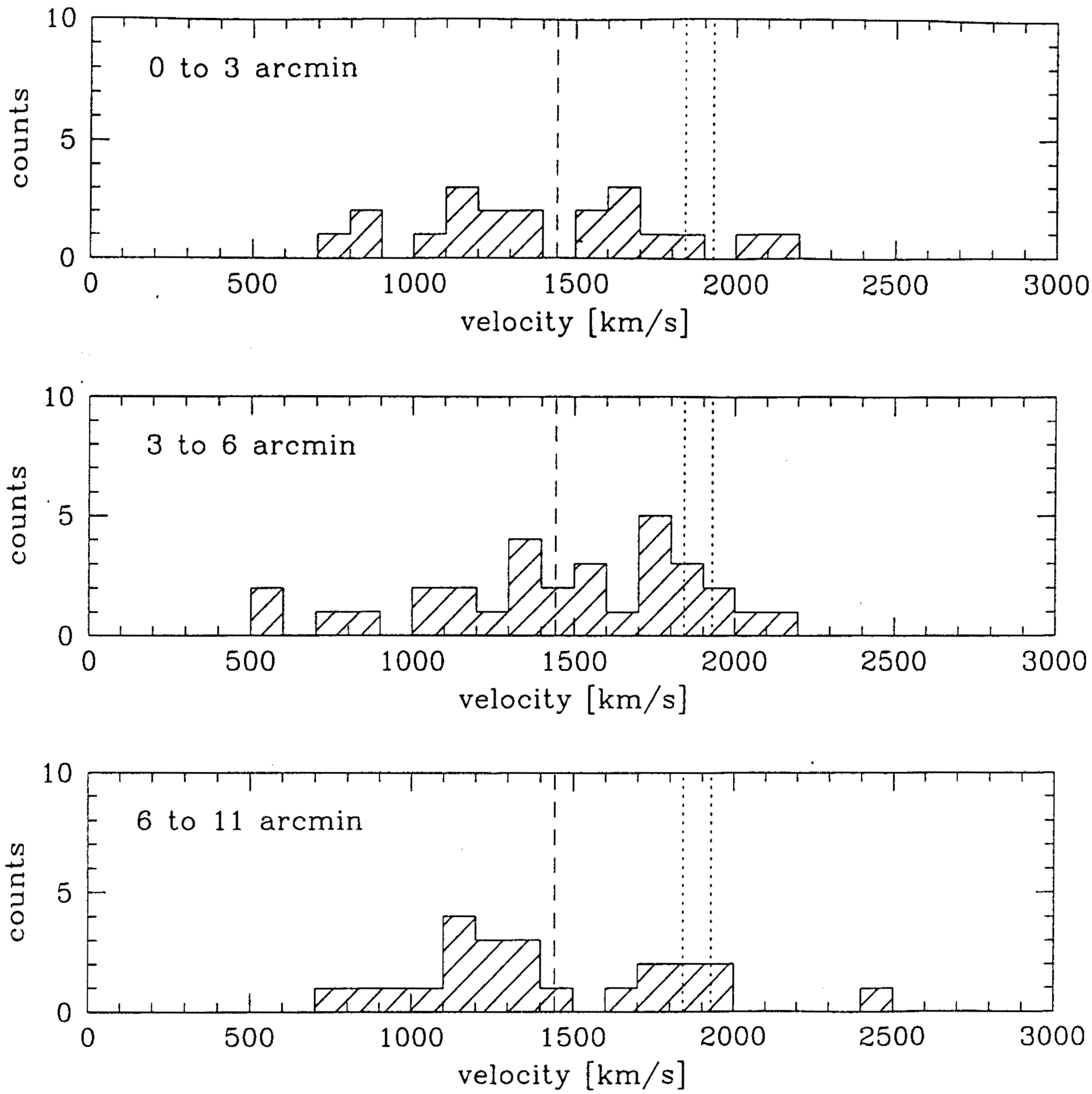

Fig. 4.— Same as Fig. 2, except that the full sample was divided into three radial bins: 0'–3' (top), 3'–6' (middle), and 6'–11' (lower panel), and no distinction was made between the AAT, NTT, and Keck samples.

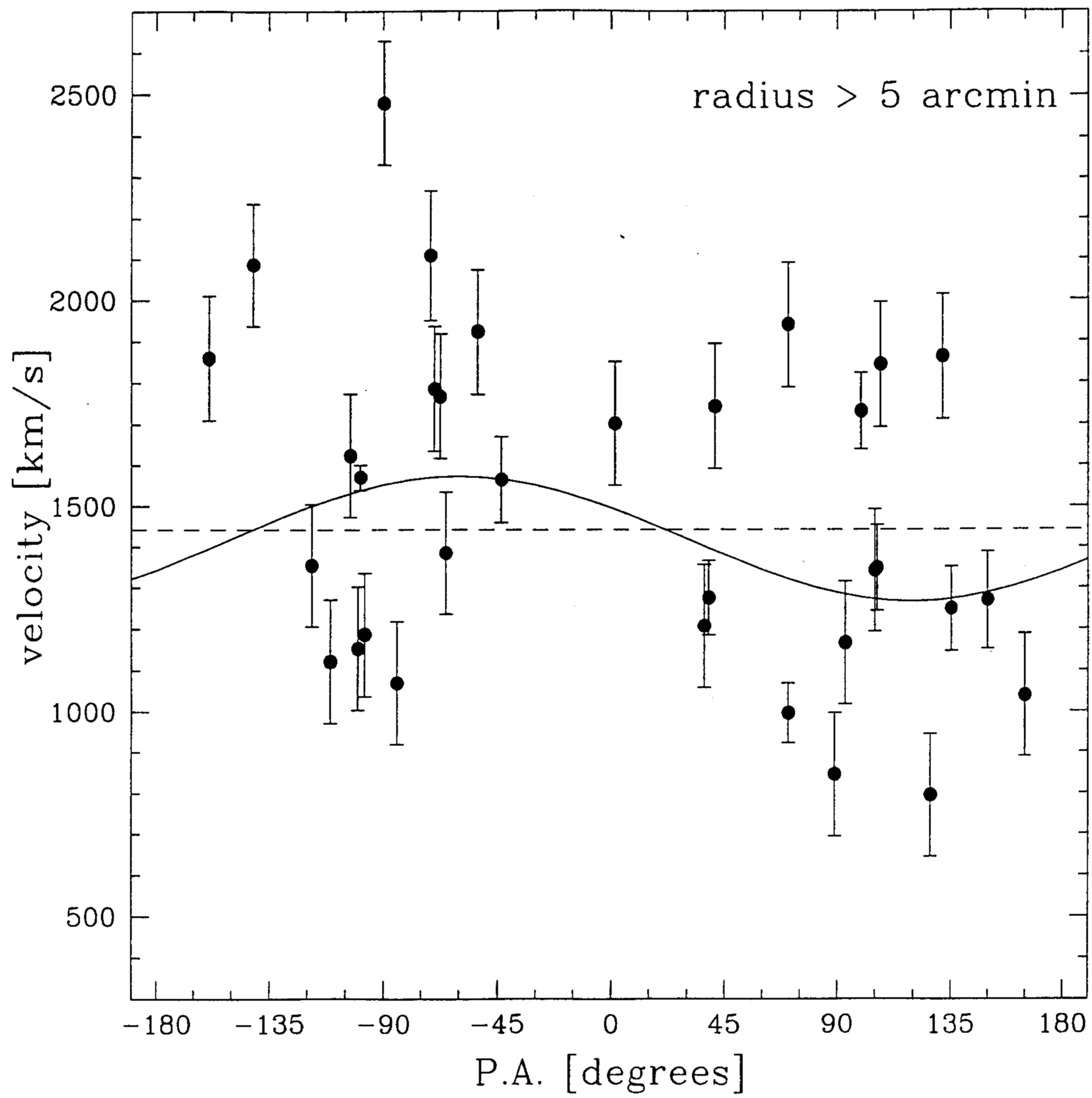

Fig. 5.— The velocities of the 33 globular clusters at a distance greater than 5' from NGC 1399 are plotted against their position angle. The solid line shows the best fitted rotation (amplitude: 153 ± 93 km s^{-1}, PA:120 ± 40 degrees $\simeq$ the major axis of the NGC 1399 isophotes). The long dashed line shows the systemic velocity of NGC 1399.

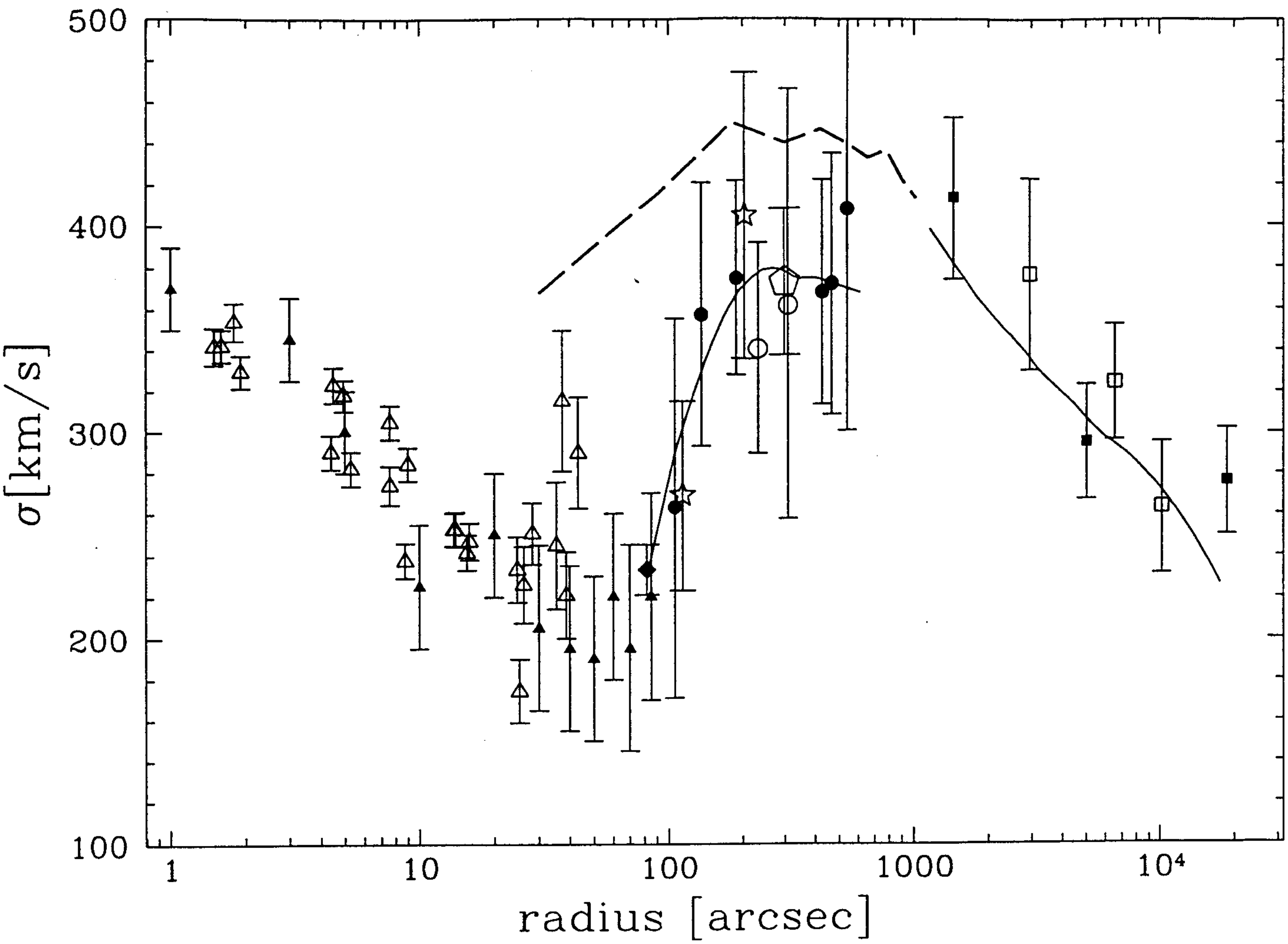

Fig. 6.— Velocity dispersion versus radius for various components. Triangles show the velocity dispersion of the stellar light taken from Franx et al. (1989, solid symbols), Bicknell et al. (1989, open symbols), and Winsall & Freeman (1993, diamond); the stars show the velocity dispersion of planetary nebulae at two radii taken from Arnaboldi et al. (1994); the filled circles mark the velocity dispersion of our different radial sub-samples, the open circles mark the velocity dispersion of the red and blue sub-samples, the pentagon marks the velocity dispersion of the entire sample (data from Table 3); the squares show the velocity dispersion of Fornax galaxies, taken from Hartog & Katgert (1996, filled symbols) , and Ferguson (1989, open symbols). The solid line represents the LOWESS fit to the globular cluster and galaxy data. The dashed line shows the velocity dispersion profile derived from the temperature of the X-ray gas (Jones et al. 1997).